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***PROFILE NEGOTIATION:  
A CONCEPT FOR INTEGRATING AIRBORNE AND GROUND-BASED  
AUTOMATION FOR MANAGING ARRIVAL TRAFFIC***

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## **1 INTRODUCTION**

In the past, the development of airborne flight management systems (FMS) and ground-based air traffic control (ATC) systems has tended to focus on different objectives with little consideration for operational integration. For example, the airborne FMS is designed to provide planning capability to optimize an individual aircraft's horizontal and vertical paths. Some newer systems even have limited time-based (4D) planning capability which enables the aircraft to meet prescribed arrival times. Comparatively, ATC has the objective to provide for a safe, orderly, and expeditious flow of traffic; the critical factor being the maintenance of separation between aircraft. Unfortunately, the objectives of individual flightpath optimization and traffic separation are often contrary in today's airspace system. Furthermore, controllers have no automation tools to predict separation 10 minutes or more into the future, let alone tools to assist in setting up nominally conflict-free descent trajectories. When arriving at high density terminal areas, aircrews are often unable to take advantage of their FMS optimization capability because ATC instructions interrupt their FMS planned trajectories. This barrier to FMS utilization not only reduces the fuel savings potential of FMS operations, it is also a major factor inhibiting the deployment of more advanced flight management systems, in particular those with 4D capability.

Successful integration of air and ground automation systems would realize several operational advantages. In addition to improving the operating efficiency of individual aircraft, the FMS offers significant potential to enhance ATC operations. If a time-based ATC system was able to plan conflict-free arrival times, as well as nominally conflict-free trajectories to meet those times, the airborne FMS would serve well as an instrument for executing that plan. An airborne 4D system is the most accurate means of meeting a prescribed arrival time; experimental studies have shown that airborne 4D systems can achieve arrival time accuracies on the order of five seconds (ref. 1). Furthermore, the FMS could provide the most accurate means of tracking a desired trajectory. FMS equipped aircraft could also serve as flow markers for surrounding traffic of less capability. If ATC took advantage of the FMS to improve its prediction and control of aircraft trajectories, separation standards may be relaxed for the same level of safety. This in turn would provide greater flexibility for the FMS to perform optimum trajectory planning for individual aircraft.

The key technical challenge is the creation of an integrated air/ground environment whereby ATC can fulfill its objective efficiently and yet allow pilots maximum discretion to take advantage of the unique capabilities of their aircraft. This environment requires the development of compatible airborne and ground-based (ATC) automation systems as well as procedures designed to complement FMS operations (4D in particular).

A joint program between NASA's Ames Research Center (Ames) and Langley Research Center (Langley) is underway to investigate the issues of, and develop systems for, the integration of ATC and airborne automation systems. Ames has developed the Center/TRACON Automation System (CTAS), a ground-based 4D ATC automation system designed to assist controllers in the efficient handling of traffic of all types and capabilities. This system, recently selected by the FAA for field test implementation, has the ability to accurately predict aircraft trajectories and determine effective advisories to assist the controller in managing traffic. CTAS provides a minimum 4D capability for all aircraft while simultaneously adapting the trajectory information to meet the needs of the controller. Langley has been conducting and sponsoring research on flight operations of advanced transport aircraft for a number of years. During the course of this research, operational issues have been a primary concern including the practical implementation of 4D flight management concepts to permit fuel efficient operations in a time-based ATC environment. The Ames/Langley joint program is in its second phase, the focus of which is the development and evaluation of the profile negotiation process (PNP). The PNP is an interactive process between an aircraft and ATC which combines airborne and ground-based automation

capabilities to determine conflict-free trajectories that are as close to an aircraft's preference as possible.

This paper presents the PNP concept as it is applied to the management of arrival traffic within the extended terminal area up to, but not including, Terminal Radar Approach Control (TRACON) airspace. Although the emphasis is on 4D capability, much of the discussion may be applied to FMS operations in general. The paper begins with a background discussion on several pertinent air/ground system integration issues including results from the first phase of the Ames/Langley program. The PNP concept will be described and some preliminary results from a real-time simulation study given. This paper focuses on functional issues from the ground-based perspective; airborne and communications related aspects are not presented in any detail. More detailed technical descriptions of the development and evaluation of the PNP, including airborne, ground-based, and communications (datalink) issues will be forthcoming in NASA Technical Memoranda to be published.

## **2 BACKGROUND**

### **2.1 Arrival Operations and the FMS**

At least two conditions are required to effectively use the FMS for flightpath optimization: the FMS must be able to incorporate ATC instructions in its trajectory planning; and ATC interruptions to the planned trajectory must be minimized. With regard to the first condition, today's flight management systems are able to handle most ATC instructions including the crossing restriction. This ATC instruction requires an aircraft to meet altitude and speed restrictions at a fix, and is useful for the separation of crossing traffic as well as the merging of arrival flows. With regard to the second condition, few interruptions occur during periods of light traffic. However, during periods of moderate to heavy traffic, interruptions to planned trajectories occur often as controllers work to maintain separation and expedite the flow. If the interruptions are outside of the flight management system's ability to adapt, or if they are beyond the aircrew's ability to reprogram the FMS, the effectiveness of FMS flightpath optimization is significantly reduced. A major goal of air/ground system integration is to minimize these interruptions in terms of the number that occur as well as their individual effect on flightpath efficiency.

Interruptions to FMS planned flightpaths are mostly due to the methods currently used by Air Route Traffic Control Center (Center) controllers for managing arrival traffic. The two primary methods for handling moderate to heavy arrival traffic at major terminal areas include intrail spacing and metering. While both methods must provide for the minimum legal separation between aircraft, each method attempts to regulate the arrival flow differently. These methods will be described briefly here; a more detailed description of these methods, and their use at the Denver Center, may be found in reference 2.

The spacing method adjusts intrail separation (above minimum legal standards) to handle the compression and merging of arrival flows. General intrail spacing requirements are determined by prior agreement within and/or between ATC facilities. Spacing requirements are adjusted, as needed, based on the traffic conditions (e.g. 10, 15, or 20 n.mi. intrail). For a given spacing requirement, controllers adjust the aircraft's speed, altitude, and horizontal path to achieve the desired spacing. These adjustments lead to the interruption of FMS planned trajectories.

The metering method is used at some major hub terminals such as Denver and Dallas Ft. Worth. This method, supported today by the Arrival Sequencing Program (ASP), is an early form of time-based traffic management. ASP is a continuation of enroute metering (ERM), which attempts to control the traffic flow through the assignment of metering fix (MF) arrival times.

For the most part, the metering process is transparent to the pilot (i.e. the pilot is not given responsibility for meeting the MF time). ATC typically issues MF crossing restrictions and then adjusts each aircraft's speed, altitude, and horizontal path prior to the MF to maintain minimum separation and meet metering requirements. Like the spacing method, these adjustments also lead to interruptions which reduce the effectiveness of FMS flightpath optimization.

One expectation associated with time-based operations is the ability for aircraft to effectively use 4D FMS capability. In an ideal world, arriving 4D aircraft would receive an assigned MF crossing time while still at cruise and then plan their speed and descent to meet the MF time and minimize fuel burn. Unfortunately, this expectation has not been fully realized. For the most part, 4D operations do not occur today, even with ASP. This is due to at least two major reasons. To begin with, there are no ATC "4D" procedures that exist today; many controllers are not even aware of this capability or of the aircraft that are equipped. The second, and more significant barrier to current day 4D operations is the poor precision of MF arrival times. 4D aircraft must receive a precise MF arrival time assignment, prior to descent, that is at least conflict-free at the MF. Under ASP, it is possible for two aircraft to be scheduled at the MF at the same time (MF arrival times are rounded to the minute on the controller's display). In addition, the ASP sequence often does not correspond to the sequence set up by the controller. As a result, controllers only use the MF times as a secondary goal and give first priority to relative spacing. The controller sets the sequence, maintains separation, and tries to feed one aircraft through the MF for each ASP time slot. Furthermore, today's controller has no automation assistance to help unequipped aircraft meet their MF arrival times. The typical MF arrival time accuracy for unequipped aircraft is on the order of two minutes. Given today's ATC environment, and mixed traffic conditions (4D equipped and unequipped), it is all but impossible to determine precise MF arrival times for 4D equipped aircraft and to assure separation at the MF.

However, recent developments in ATC automation have the potential to resolve these problems. The ability to schedule conflict-free arrival times based on variable traffic conditions and controller preferences has been demonstrated using CTAS (ref. 3). More importantly, automation tools have been developed to assist the controller in achieving arrival time accuracies, for unequipped aircraft, on the order of ten and twenty seconds in the TRACON and Center respectively (refs. 4-6). These capabilities are the foundation for any ATC automation system which attempts air/ground integration for time-based ATC operations.

One additional issue concerns the capability of 4D equipped aircraft to accurately track a 4D trajectory. Commercial 4D systems flying today have the capability to generate trajectories based on cost index (a ratio of time and fuel costs). These systems meet an arrival time constraint by iterating on cost index until a trajectory solution is obtained which satisfies the arrival time constraint. Closed-loop guidance to achieve the desired arrival time is accomplished by recomputing the vertical trajectory when time error exceeds a predefined level. There are no provisions to constrain the cruise and/or descent speeds chosen to achieve the desired arrival time. As a result, the aircraft may fly a substantially different vertical trajectory than the one originally planned to meet the time.

The airspace which would be required to maintain separation for one 4D aircraft using this guidance method could easily prohibit a sequentially neighboring aircraft from exercising the same capability. For practical 4D FMS operations in a high density terminal area, the capability to accurately track a given trajectory in four dimensions is probably as important, if not more, than the capability of an FMS to generate optimum trajectory plans. Research conducted and sponsored at Langley is not only investigating 4D trajectory generation techniques, but also developing guidance concepts for piloted and automatic trajectory tracking (refs. 7-9).

## **2.2 Ames/Langley Joint Program**

The Ames/Langley program was created in 1989 to develop and evaluate airborne and ATC automation systems for air/ground system integration. The program began with a baseline technology which combined the individual automation systems developed at Ames and Langley up to that time: ATC automation (CTAS) from Ames; and airborne flight management systems from Langley. The capabilities of this baseline technology addressed most of the major obstacles to current day 4D FMS operations listed above. In particular, CTAS would provide conflict-free arrival time scheduling as well as controller advisories to help unequipped aircraft meet that schedule. On the airborne side, 4D guidance automation would assist the pilots of 4D equipped aircraft in both planning a 4D trajectory to meet an assigned MF time and accurately tracking that 4D trajectory plan.

The purpose of the program's first phase was to evaluate the baseline technology by introducing a 4D FMS equipped aircraft into a time-based ATC environment and exploring the resulting situations and problems. The associated experimental study (4D Aircraft/ATC Operations Study, July 1989) focused on the compatibility of airborne and ATC systems when dissimilar 4D strategies were used. Dissimilarity in 4D strategies refers to differences in the speed profiles (combinations of cruise and descent speed) chosen by the ATC and airborne automation to meet an assigned arrival time for a given routing. In the case of CTAS, trajectory solutions are fuel conservative in that they minimize level flight at lower altitudes; speed profiles are chosen to meet controller constraints. Dissimilarity occurs because airborne systems are designed to find the fuel optimal speed profile for a fixed time. Candidate procedures for handling 4D equipped aircraft were developed and traffic scenarios were devised to create specific air traffic problems and delays. The study was conducted through 30 hours of real-time simulation using active controllers and airline flight crews as test subjects. A brief summary of results will be given here; more detailed descriptions of the experiment, from the airborne and ground-based perspectives, are presented in references 10 and 11.

In general, the 4D procedures were well received by the controllers and pilots. The controllers responded favorably to the CTAS tools and were effective in meeting the CTAS sequence and schedule; the pilots of the 4D aircraft achieved an arrival time accuracy indicated by a time error of negligible mean and a standard deviation of 2.9 seconds. Under conditions of medium delay (delays requiring vectoring, but not necessarily holding), the 4D FMS demonstrated an operational benefit. For the scenarios tested, pilots were able to consistently fly ATC vectors to absorb the delay while using the FMS to find the optimum point to return to an arrival routing.

However, under conditions of small delay (delays which could be absorbed using speed control only), dissimilar speed strategies often lead to a loss of minimum separation prior to the metering fix. To maintain separation, controllers interrupted the descents of one or more aircraft, usually including the 4D equipped aircraft. For the cases studied, the 4D aircraft's minimum fuel solution had the potential to save 39 lbs (2.2%) of fuel per flight over the basic uninterrupted ATC (CTAS) solution. However, ATC interruptions to the 4D aircraft's optimal trajectory plan caused the actual fuel burn to average 111 lbs (6.3%) more per flight than the basic uninterrupted ATC solution. Controllers found it very difficult to predict, let alone resolve these conflicts prior to issuing a metering fix arrival time clearance. The increase in fuel burn and added workload associated with the interrupted profiles negated the potential gains from the 4D aircraft flying its own fuel optimal trajectory. The experiment also investigated offset routing to allow sequentially scheduled aircraft to maintain separation while flying substantially different speed profiles. Results indicated that, for the geometry studied, it was more efficient for a 4D aircraft to adopt the ATC system's (CTAS) speed strategy than to attempt to use dissimilar speeds.

In summary, the July 1989 study fostered new insight into the minimum system requirements necessary to support 4D FMS operations. The ATC automation must do more than schedule

conflict-free arrival times and provide controller advisories for unequipped aircraft. Specifically, the ATC automation must also probe the airspace for potential conflicts (loss of minimum separation) while incorporating FMS solutions in the analysis. If a potential conflict is predicted, the ATC automation must work with the controller to determine acceptable 4D trajectory solutions that are nominally conflict-free and still meet the assigned arrival time. 4D aircraft must then be able to follow an ATC derived 4D solution using the FMS for accurate tracking. Digital datalink technology would be ideally suited for the task of exchanging trajectory data between airborne and ATC automation systems. However, the minimum data required to adequately define 4D trajectory solutions must still be determined. In addition, the ATC automation should provide the controller with delay advisories in the horizontal plane (pathstretching) to complement speed and descent advisories in the vertical plane.

The purpose of the second phase of the program was to develop systems and procedures to address the issues described above. ATC automation development focused on conflict prediction, conflict resolution, pathstretching, and the analysis of trajectory information downlinked from a 4D equipped aircraft. An air/ground digital datalink communications capability was also developed to enable the two-way exchange of trajectory data. Airborne automation development included the addition of a 4D trajectory generation mode which adapts to ATC 4D trajectory constraints, incorporation of automatic 4D pathstretching for trajectory planning, and integration of FMS trajectory information into the digital datalink system. The main emphasis of phase two is the implementation of the profile negotiation process. The PNP concept is presented next, followed by a description of the ground-based aspects of its implementation into a laboratory research system.

### **3 PROFILE NEGOTIATION PROCESS**

Profile negotiation is a simplification of the more general process of trajectory negotiation. The purpose of trajectory negotiation is to determine a "valid" trajectory which is as close to the aircraft's preference as possible. A valid trajectory is one which satisfies all ATC constraints, particularly separation. The aircraft's preferred trajectory may be determined by the pilot, company procedure, or FMS optimization. Trajectory negotiation is "strategic" in that it defines a future, or planned, trajectory to be followed under expected conditions (e.g. traffic, weather). Tactical deviations may occur, or a new strategic plan formed, to meet unexpected conditions. However, the better the strategic planning, and the better a plan can be executed (through accurate trajectory tracking by aircraft), the greater the likelihood that a negotiated trajectory may be followed without significant interruption.

The negotiation process assumes the standard roles for the pilot and ATC. The pilot, acting as the final authority concerning the operation of the aircraft, may request or negotiate ATC clearances at any time. However, since ATC is responsible for maintaining separation between traffic (under instrument flight rules), ATC must assume the role of arbiter and strike a compromise between the preferences of conflicting aircraft. The concept of trajectory negotiation formalizes this compromise into an objective process which is ideally suited for automation as well as optimization (e.g. minimization of fleet fuel consumption). This study does not address optimization directly, but instead focuses on the realization of the negotiation process itself.

4D trajectories are uniquely characterized by three profiles: the horizontal path, or ground track; the altitude profile along the horizontal path; and the speed profile. For convenience, a vertical profile is defined as the composite of the altitude and speed profiles along the horizontal path. For the purposes of ATC, an aircraft's horizontal path is constrained by its assigned routing which is typically determined by the controller independently of the vertical profile. This simplifies the process of synthesizing a 4D trajectory to that of synthesizing a vertical profile.

Given a pre-determined routing, the PNP attempts to find a valid vertical profile that is as close to the aircraft's preference as possible. The PNP complements current generation FMS optimization methods which also search for a vertical profile solution for a pre-determined routing. The PNP may also be applied to cases of partially determined routing. An example of partially determined routing occurs when a controller vectors an aircraft, to absorb a delay, with the intention of returning the aircraft to a predetermined routing. This method for absorbing delay is referred to here as pathstretching. The undefined portion of the aircraft's routing is directly related to the vertical profile in that the length of the delay vector is directly related to the speeds chosen. The PNP may be applied to any combination of flight segments: climb, cruise, and descent. This paper focuses on the final cruise segment and descent to a terminal area metering fix.

The PNP is best described in terms of the air/ground interaction that would occur during a typical arrival scenario into an advanced time-based ATC environment (figure 1). An advanced time-based ATC environment (e.g. CTAS) is one which employs automation that not only determines conflict-free arrival times but also determines conflict-free 4D trajectories to meet those times. As the aircraft enters the extended terminal area (approximately 200 n.mi. or 40 minutes from touchdown), it enters a scheduling process. The scheduling process (figure 2) defines the arrival time constraint for the PNP. In the most general case, ATC would query the pilot for the desired arrival time based on a nominal routing and the pilot would respond with the FMS solution. ATC records the pilot's proposal and compares it to the desired arrival times of the other arrival traffic to determine the best overall sequence and arrival schedule. Once scheduled, the aircraft enters the profile negotiation process to determine a 4D trajectory solution which is conflict-free, meets the arrival time, and is as close to the aircraft's preferred vertical profile as possible. This trajectory solution is transformed into a clearance for the pilot to execute using the FMS for precise tracking.

The profile negotiation process is illustrated in Figure 3. The PNP begins when the controller requests a vertical profile proposal from the pilot. This request contains a list of all known ATC constraints including the assigned arrival time and any additional items determined by the controller (e.g. routing). The controller always decides the degree of freedom each profile request will allow the pilot for generating a profile proposal. In the case of a delay requiring pathstretching, the controller may allow the aircraft some flexibility on the length of the delay vector based on the aircraft's preferred speeds. This process assumes the same procedures, used today, for the issuance and acceptance of ATC clearances: the pilot may negotiate with the controller to modify unacceptable constraints as required.

After receiving the profile request, the pilot uses the FMS to compute a preferred vertical profile solution. This airborne solution must meet all ATC constraints and may also reflect additional constraints determined by the pilot. The resulting vertical profile is then transmitted to the controller for consideration, and entered into the ATC computer when convenient. In considering the pilot's proposal, the controller uses the ATC automation to check for potential conflicts with other aircraft all the way to the metering fix. If no conflicts are predicted, the controller issues a 4D clearance based on the aircraft's preferred vertical profile. The pilot then uses the FMS to execute the clearance and track the 4D trajectory.

If a conflict is predicted, the controller uses the ATC automation to determine the minimum modification to the aircraft's proposed vertical profile that is necessary to avoid any predicted conflicts. The resulting 4D trajectory solution may be implemented in one of two ways. One option for the controller is to issue the entire 4D solution as an arrival clearance for the aircraft to execute. This is useful when there is little time for fine adjustments (e.g. when the aircraft is near its top of descent, or the controller's workload is heavy). The second option is to issue "tactical" instructions (speed, heading, and/or altitude assignments) to implement the first portion of the controller's trajectory solution, and leave the rest of the clearance to be issued later. The

advantage of this second option is that it allows the controller to make a gross correction to the aircraft's profile quickly and fine tune the final 4D solution later. This technique is useful for balancing workload between sectors when multiple sectors work together to sequence arrivals in a "high/low" configuration.

The PNP is performed by the controller on a workload permitting basis only. It may be simultaneously applied to any number of aircraft capable of supporting the negotiation process. The word negotiation is used to emphasize the role of the pilot and FMS in determining a valid trajectory solution which would not necessarily be the first choice of ATC, but nevertheless would be acceptable. In general, the PNP is initiated by the controller following the scheduling process. However, pilots may also request the controller to consider an unsolicited vertical profile proposal. The controller may discontinue negotiation at any time and handle the traffic in a conventional manner. Even if discontinued, profile negotiation offers the advantage of having reduced the number of potential conflicts that must be resolved in the future.

The PNP incorporates the major advantages of airborne and ATC automation in a complementary fashion. The FMS performs two tasks in support of the PNP: trajectory optimization, which is of primary concern to the aircraft operator; and trajectory tracking, of primary concern to ATC. The ATC automation performs the critical task of analyzing the airborne proposal and ensuring a nominally conflict-free solution (separation being the primary responsibility of ATC). Of the two tasks performed by the FMS, the importance of accurate 4D trajectory tracking cannot be overstated. If an aircraft cannot accurately track a negotiated trajectory, it increases the risk of ATC interruption to its negotiated trajectory as well as the planned trajectories of sequentially neighboring aircraft. Since interruptions may significantly reduce the potential benefit of trajectory optimization, there is little purpose in attempting trajectory optimization without adequate tracking capability. The definition of what constitutes adequate trajectory tracking has yet to be determined; the definition of minimum 4D tracking requirements is an important area for future research. The technical issue of interest here is the development and evaluation of the automation tools necessary to assist the pilot and controller in performing the PNP in an effective and low workload manner.

## **4 PNP IMPLEMENTATION**

The major elements necessary to implement the PNP include the airborne automation systems (FMS), the ATC automation tools, and a communications medium which enables the airborne and ATC systems to exchange trajectory data. This paper concentrates on the ground-based aspects of the PNP implementation, specifically with regard to using CTAS as the foundation for the ATC automation.

### **4.1 Center/TRACON Automation System (CTAS)**

CTAS is an integrated set of automation tools designed to assist controllers in the efficient management and control of arrival traffic. It has been implemented in the laboratory on a series of workstations connected by a local area network. CTAS is comprised of three major toolboxes: the Traffic Management Advisor (TMA); the Descent Advisor (DA); and the Final Approach Spacing Tool (FAST). The TMA assists traffic managers in the Center and TRACON with the sequencing and scheduling of traffic; the DA assists Center controllers in efficiently meeting the TMA's schedule while maintaining separation; and FAST assists TRACON controllers in fine-tuning the arrival flow. Implementation of the PNP primarily involves the DA which will be described in more detail. Additional information on the TMA is provided in reference 3, and a thorough description of the design and evaluation of FAST is provided in references 4 and 12.

## 4.2 Descent Advisor (DA)

The DA is designed to assist the Center controller in accurately and efficiently delivering arrival traffic to the TRACON feeder gates in accordance with the TMA's schedule. The heart of the DA is a generic 4D trajectory generation algorithm which is adaptable to different types of aircraft. It contains detailed models of aircraft performance and operational characteristics, and takes advantage of all real time inputs of atmospheric data available in its area of operation. The DA continuously re-synthesizes 4D trajectory solutions for all arrivals based on controller inputs, aircraft state (from radar tracking), and the TMA schedule. The DA translates these trajectory solutions into controller advisories which include speeds for cruise and descent, top of descent, and heading. The DA monitors the traffic, including overflights, and compares the trajectories it predicted for each aircraft. The controller is advised of any potential conflicts that are predicted up to 20 minutes, or more, in advance. The DA also provides continuous feedback on whether or not subsequent controller actions resolve the predicted conflicts. In effect, potential conflicts are resolved far in advance of the time a controller would have normally detected them without assistance from the DA.

The DA's functions are interfaced with a mouse-based, menu-driven controller display. The display features include those available on current Center plan view displays (PVD), as well as color, timeline, and other advanced graphical features. A mouse pointer, or trackball, is used by the controller to select display objects including aircraft symbols, tags, and fixes; the controller invokes the DA's functions via on-screen "buttons" or keyboard inputs. Additional information on the development and evaluation of the DA, its functions, and controller interface, may be found in references 1-3, 5, and 6.

Modifications to the DA in support of the PNP included the addition of two functions: Trajectory Re-creation; and Conflict Resolution. Trajectory Re-creation allows the DA to re-create an airborne trajectory solution based on the data transmitted by the pilot either by voice or datalink. This allows the DA to analyze airborne solutions for potential conflicts. Conflict Resolution determines a nominally conflict-free trajectory solution for an aircraft when its original solution is predicted to be in conflict with the trajectories of other aircraft. The development of these modifications followed the same guidelines for ATC automation development outlined for CTAS in reference 3. Among others, these guidelines advise not to automate complex or poorly understood tasks; to apply automation to complement controller's skills; and to involve controllers in the selection and design of automation tasks from the start. The application of these guidelines is described next.

The task of planning descent trajectories which are conflict-free far into the future (20 minutes or more) is a complex problem which is dependent on controller technique and preference. Controllers are highly skilled at solving tactical traffic problems given today's graphical displays. On the other hand, computers are well suited for the high speed computation necessary for longer range strategic planning which depends on accurate modelling of aircraft performance and atmospheric characteristics. For these reasons, the Trajectory Re-creation and Conflict Resolution functions were developed with a low level of automation. While this allowed the controller maximum adaptability, it also required active controller participation. For example, the Trajectory Re-creation function was designed to be invoked manually by the controller because it was not clear when, and under what circumstances, the function should be invoked automatically. This way, the controller decides when airborne trajectory solutions are to be analyzed. The Conflict Resolution function was also designed to be invoked manually. There are few tasks, if any, which are more challenging than "strategic" conflict resolution. Predicted conflicts within moderate to heavy density traffic usually require modification to more than one aircraft, and typically, many "valid" solutions exist. The controller selects which aircraft to modify as well as the type of modification (speed, altitude, or routing). Until this problem is better understood, controller inputs are required to constrain the computer to solutions that follow

the controller's preferences. Following the guidelines listed above, the DA's display and interface were designed to allow the controller to solve problems graphically while the computer calculated the precise solutions. Once controller preferences and techniques for planning conflict-free 4D trajectories are better understood, the task of profile negotiation will be simpler to automate at a higher level.

## 5 PNP EVALUATION

The PNP was evaluated in a real-time ATC simulation (4D Aircraft/ATC Integration Study, May 1991). The ATC environment was simulated at Ames using CTAS for 4D traffic management while the 4D FMS equipped aircraft was simulated at Langley using the Transport Systems Research Vehicle (TSRV) 737 piloted cab. The TSRV cab was connected to the Ames simulation via voice and data communications lines. The remainder of the traffic (non-4D equipped) was simulated at Ames using a pseudopilot aircraft simulation (ref. 2). Air/ground communications, for conventional as well as PNP (trajectory exchange) purposes, were supported by both voice and digital datalink media. Three teams of active Center controllers (2 each) and three crews of line pilots (2 each) participated as test subjects in 30 hours of simulation.

The simulation airspace was based in part on the Denver area. Arrival traffic for the Denver Stapleton airport was simulated from two directions: northeast (NE) and northwest (NW), and was scheduled for a coordinated feed into the TRACON. NW traffic was light and handled automatically; NE traffic was of moderate density (36 arrivals per hour plus overflights) with delays of three to eight minutes, and handled by one controller team for each run. The NE airspace was divided into a High/Low configuration with one controller handling the High sector (approximately 100-200 n.mi. from Denver) and the other controller handling the Low sector (approximately 30-100 n.mi from Denver). The traffic scenarios ended at the TRACON hand-off.

The controllers were tasked with meeting the TMA's arrival schedule at the metering fix while maintaining separation. For each traffic scenario, the TSRV was injected into the arrival flow at a predetermined time to create a specific traffic problem for the controller team in terms of handling a 4D equipped aircraft. Equivalent traffic scenarios were repeated by each controller and pilot team with and without digital datalink communications. A standard atmosphere with calm winds was used with no modelling errors (i.e. no differences between the actual atmospheric conditions used and the conditions modelled by the airborne and ground-based automation). Analysis of the experiment is currently underway with the results to be published in a future NASA TM. A typical conflict problem will be presented here, along with one of the actual PNP solutions executed by the controller and pilot test subjects.

### 5.1 PNP Scenario Example

The following example will serve to illustrate the practical application of the PNP. Figure 4 illustrates a set of traffic conditions which lead to a potential conflict during one traffic scenario. Three sequentially scheduled aircraft are shown with the surrounding aircraft removed for clarity. The aircraft enter the airspace from the northeast with the initial cruise conditions tabulated in figure 4. The aircraft in the middle of the sequence is the 4D equipped TSRV piloted cab. The aircraft sequenced in front and behind, referred to as the LEAD and TRAIL aircraft respectively, are not FMS equipped.

Before the PNP begins, the aircraft are scheduled by the TMA based on their desired times of arrival and the traffic load. For this case, the 4D aircraft's desired time of arrival at the metering fix is 29 minutes after the hour. The desired times of arrival for the LEAD and TRAIL aircraft

are 31 seconds earlier and 85 seconds later, respectively. The desired times of arrival for the non-4D equipped aircraft are computed by the DA based on the aircraft's state when entering the scheduling process and a descent to the MF at the aircraft's preferred descent speed (a database of preferred descent speeds as a function of airline and aircraft type is contained within the DA). All three aircraft are scheduled by the TMA to be conflict-free at the metering fix with a small delay due to capacity limits.

The controller must consider the 4D trajectory solutions necessary to meet the schedule. The DA computes a solution for each aircraft, based on the aircraft's state as well as constraints input by the controller (e.g. routing), and translates the solution into controller advisories for speed and descent. The original DA vertical profile solutions for the LEAD and TRAIL aircraft are tabulated in figure 4 and are based on each aircraft's initial cruise conditions. For the LEAD aircraft, the DA advises a cruise speed reduction to 250 knots indicated airspeed (KIAS) followed by a descent at 280 KIAS; and for the TRAIL aircraft, the DA advises a cruise speed reduction to 250 KIAS followed by a descent at 230 KIAS. The corresponding tops of descent are shown on the plan view with clear symbols. Although the DA also computes a solution for the 4D aircraft, it is not shown since the solution of interest is that proposed by the 4D aircraft.

When workload permits, the controller initiates the PNP by requesting a profile proposal from the pilot of the 4D aircraft for the scheduled arrival time. The pilot enters all applicable constraints into the FMS. The FMS, like the DA, computes a 4D trajectory solution based on the aircraft's state. The 4D aircraft's profile proposal represents the FMS minimum fuel solution for the 4D aircraft at the time of the request. The profile proposal tabulated in figure 4 is based on the initial cruise conditions listed. This proposal calls for a reduction in cruise speed to 0.68 Mach (250 KIAS) followed by a descent at 230 KIAS. The corresponding top of descent is also marked by a clear symbol in figure 4.

In considering profile solutions, the controller uses the DA to predict any potential conflicts. Figure 5a depicts the predicted horizontal and vertical separation for the 4D aircraft based the 4D aircraft's profile proposal and the original vertical profile solutions for the neighboring aircraft. This figure shows the predicted compression of the LEAD and TRAIL aircraft, onto the 4D aircraft, as all three aircraft converge on the metering fix. The separation trajectories for each aircraft pair (e.g. LEAD vs. 4D) are shown starting when the horizontal separation of each aircraft pair is within 40 n.mi., and ending when the metering fix is crossed. A conflict occurs when the minimum separation boundary is penetrated.

Figure 5a shows the TRAIL aircraft starting out 4000 feet above the 4D aircraft in cruise. Although the original profile solutions for the TRAIL and 4D aircraft maintain a significant cruise groundspeed difference (27 knots), the corresponding trajectories are predicted to be nominally conflict-free. This is not the case for the LEAD and 4D aircraft. The LEAD aircraft is initially 2000 feet above the 4D aircraft. The DA's original profile solution for the LEAD aircraft calls for a cruise speed reduction to 250 KIAS (0.75 Mach), followed by a descent at 0.75 Mach to 280 KIAS. This represents the DA's attempt to find a profile solution for a non-4D equipped aircraft which is as close to that aircraft's company preferred descent speed as possible. In this case, the company preferred descent speed for the LEAD aircraft was programmed to be 280 KIAS. Although the original profile for the LEAD aircraft and the 4D aircraft's profile proposal are predicted to be conflict-free near the metering fix, their separation is predicted to fall below minimums during the descent. The inset for figure 4 illustrates the predicted conflict situation at the first point where minimum separation is predicted to be lost.

This separation analysis of the original profile solutions is performed by the DA nearly instantaneously. The DA graphically displays the situation to the controller by marking the point of predicted loss of separation on the controller's traffic display, changing the color of the aircraft tags for the aircraft involved, and listing the time to go before separation is predicted to be lost.

In this case, the problem is predicted 21 minutes in advance, far earlier than any controller would have detected the problem given today's systems.

To resolve the predicted conflict, the controller invokes the Conflict Resolution function to modify the 4D aircraft's proposal. The controller may also use the DA to simultaneously modify the profile solution for the LEAD aircraft to find a better overall compromise. In the simulation case presented here, the controller balanced the LEAD aircraft's cruise and descent speeds by decreasing the descent speed by 15 KIAS to 265 KIAS. This allowed the DA to find a nominally conflict-free profile for the 4D aircraft that was within 10 KIAS of the pilot's proposal.

The controller issued clearances based on the conflict-free profiles tabulated in figure 4. The 4D aircraft received a 4D clearance to be executed by the pilot using the FMS for tracking, whereas the LEAD and TRAIL aircraft received speed and descent instructions based on DA advisories for the profile solutions. The actual descent speed for the TRAIL aircraft (240 KIAS) differs slightly from the original DA solution (230 KIAS) because the controller decided to absorb more of the delay in cruise with a small amount of vectoring rather than descend the TRAIL aircraft at 230 KIAS. The resulting separation histories from simulation are plotted in figure 5b. The 4D aircraft was able to execute its negotiated profile without interruption.

## 5.2 Preliminary Results and Observations

The controller teams were able to consistently and effectively negotiate nominally conflict-free vertical profiles with the 4D equipped aircraft. The negotiated profiles were substantially closer to the 4D aircraft's preference than would have otherwise been possible without the PNP. However, the workload required to support the PNP (as implemented for this study) was significant. This was due in part to a short training period. The controller teams were given an average of two days training to become familiar with the PNP, 4D procedures, datalink, and the DA's functions and interface. Similarly, the 4D pilot crew training period of one half day was also short. Although more training would have significantly reduced the test subjects workload, a strong consensus among the pilot and controller teams indicated the need to increase the level of automation of the PNP tasks to make them more transparent to both the pilot and controller. This increased level of automation should consider and recommend conflict-free 4D solutions automatically with the pilots and controllers only constraining and approving the process. In addition, all subjects strongly agreed that digital datalink is preferred over voice for PNP trajectory data exchange, and that datalink should be a minimum requirement to support profile negotiation.

The ability of the airborne 4D FMS to adapt to ATC specified 4D trajectory constraints was found to be a requirement for successful execution of the PNP. The conventional method of cost index iteration for obtaining the minimum fuel 4D trajectory must be supplemented by a method which constrains the profile speeds to those desired by ATC. Without such a capability, the 4D equipped aircraft cannot participate in the PNP beyond the initial profile request stage. The controllers also indicated that the tracking ability of 4D equipped aircraft was of concern to them; if a 4D equipped aircraft could not precisely execute the negotiated profile, controllers would prefer not to spend precious time and energy accommodating a pilot's profile request.

## **6 CONCLUDING REMARKS**

The development of airborne and ground-based automation must address the issues of air/ground integration to maximize the effectiveness of the overall system. In particular, airborne automation must consider the constraints and requirements of the ATC system or risk underutilization. The effectiveness of airborne trajectory planning may be improved by reducing the net effect of interruptions to the planned trajectories. ATC interruptions may be minimized through the use of strategic planning by ATC to determine nominally conflict-free trajectories, and accurate trajectory tracking of planned trajectories by the aircraft. ATC strategic planning should consider each aircraft's trajectory preference and determine the best compromise.

The PNP, a concept for integrating airborne and ground-based 4D automation capability to improve ATC strategic planning, was implemented in a laboratory environment. A real-time ATC simulation was conducted to evaluate the PNP and explore the issues related to 4D aircraft operations in a 4D ATC environment. The PNP established an effective dialogue between the aircraft and ATC in support of 4D aircraft operations. Controller subjects indicated a strong preference for datalink over voice communications in support of the PNP. Controllers also stated their concern that the 4D aircraft must be capable of accurately tracking a 4D trajectory solution to make worthwhile the controller's time and effort required to negotiate a solution. Further development of the PNP must address workload; controller and pilot test subjects indicated the need to automate the process further without significantly reducing their ability or authority to constrain the process. However, the controllers found the DA tools to be very effective for strategic planning and tactical control, particularly when dealing with aircraft that were not 4D equipped.

Additional research is needed to determine individual and overall system requirements necessary to support 4D ATC operations, including minimum standards for 4D trajectory tracking. Another important issue concerns the modelling of aircraft performance and atmospheric characteristics; the overall system must be robust to real-world modelling errors. Future work should also investigate alternative methods for representing the aircraft's preference in the ATC strategic planning process. If the aircraft's preferred trajectory is to be generated by airborne automation in support of air/ground negotiation, the specifications for trajectory data exchange must be defined. Alternatively, the generation of preferred trajectories could be performed equally well on the ground given that critical performance data and constraints are known. Such ground-based generation of aircraft trajectory preferences could result in an additional benefit of providing trajectory optimization capability for non-FMS equipped aircraft.

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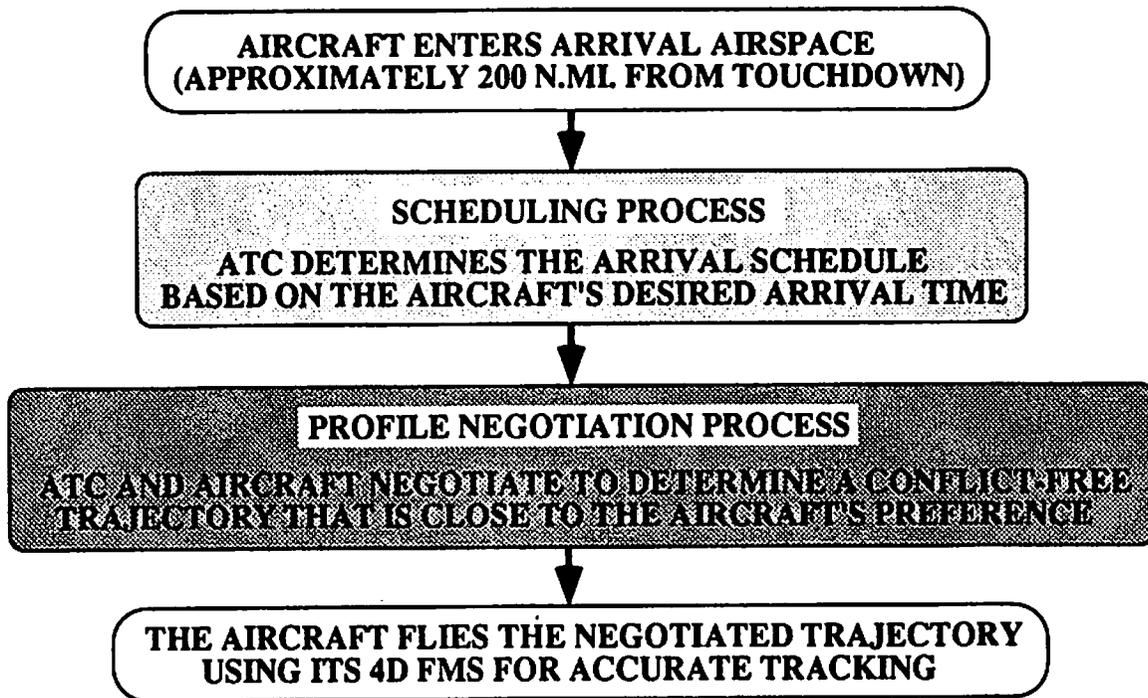


FIGURE 1. AIR/GROUND 4D INTERACTION.

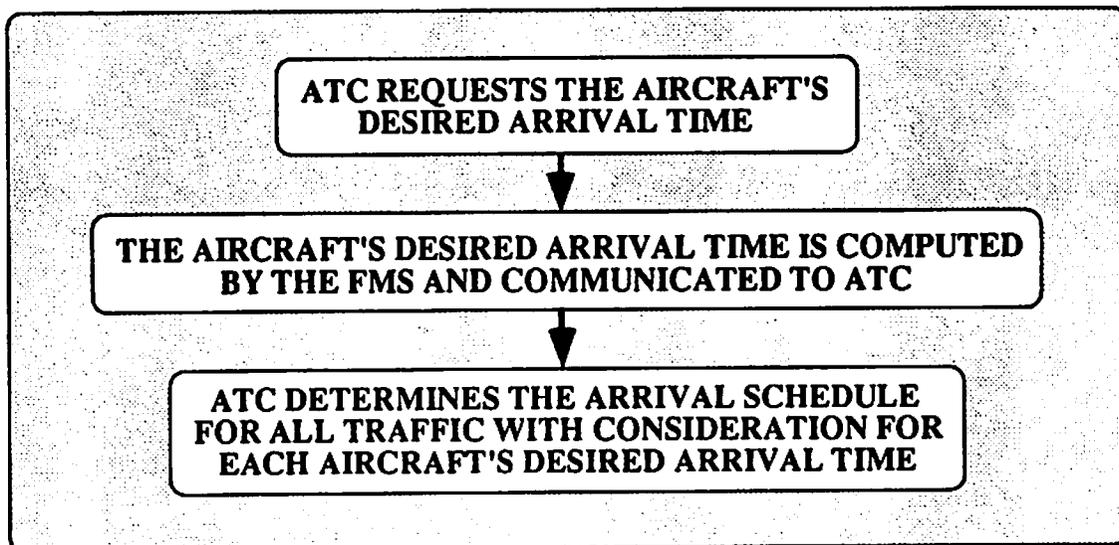


FIGURE 2. SCHEDULING PROCESS.

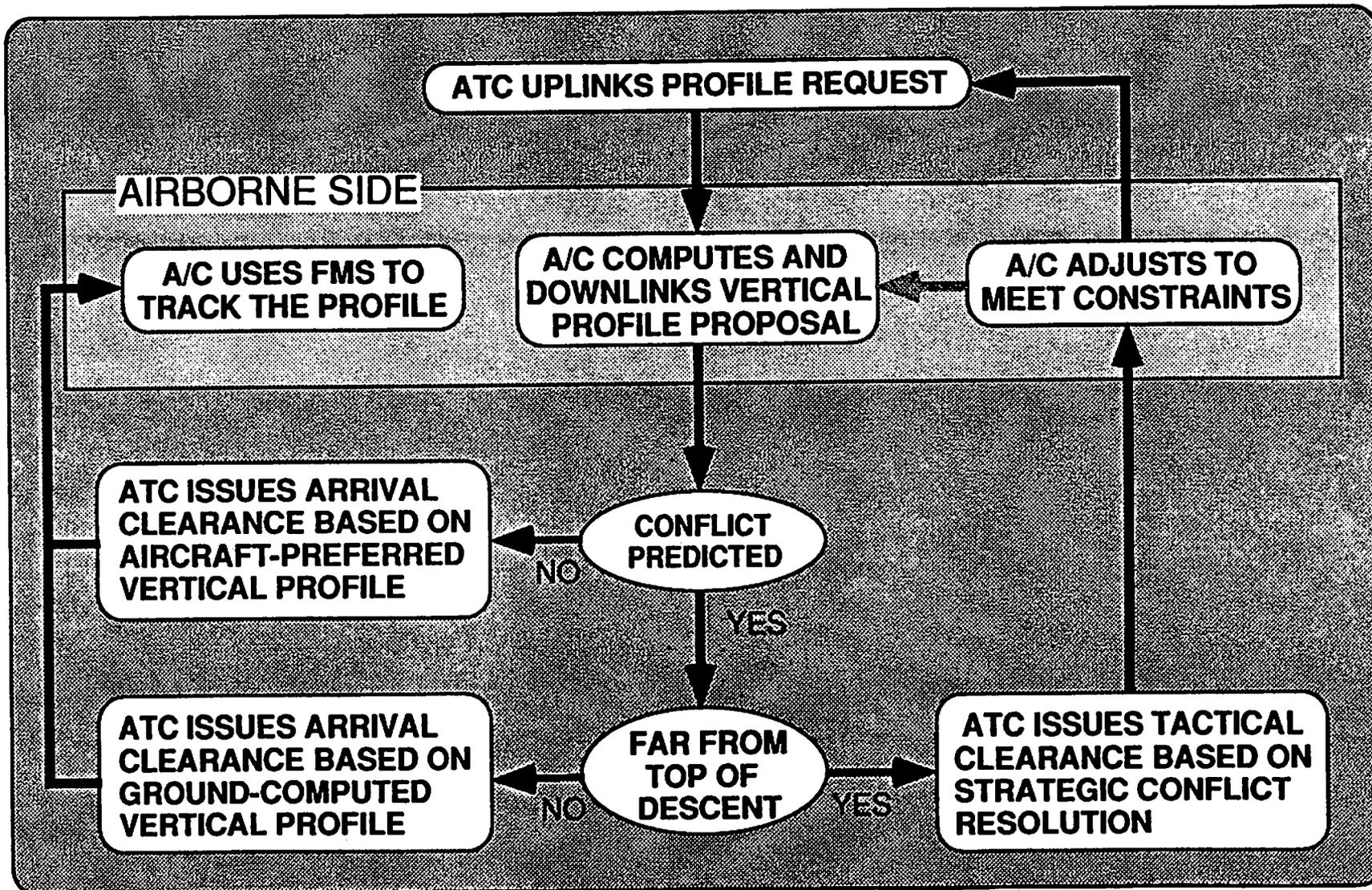
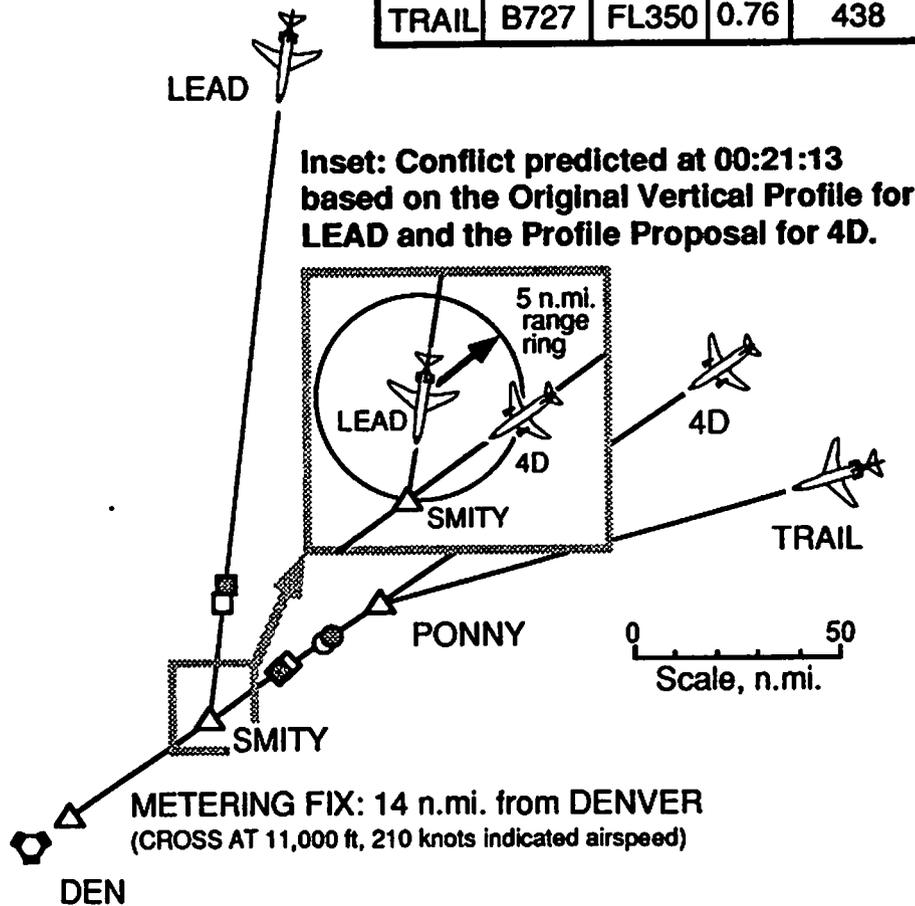


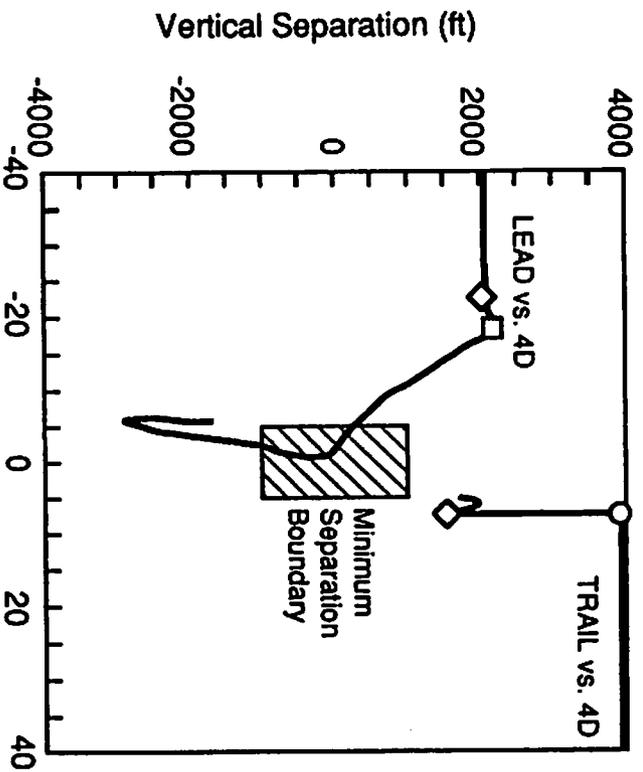
FIGURE 3. PROFILE NEGOTIATION PROCESS.

Initial Cruise Conditions						MF Arrival Times Reference (00:00:00)	
A/C	Type	Alt	Ma	Gnd Spd (knots)	Flying Dist to MF (n.mi.)	Desired	Scheduled (delay)
LEAD	B727	FL330	0.80	465	207	00:28:29	00:30:29 (2:00)
4D	B737	FL310	0.72	423	195	00:29:00	00:32:00 (3:00)
TRAIL	B727	FL350	0.76	438	200	00:30:25	00:33:25 (3:00)



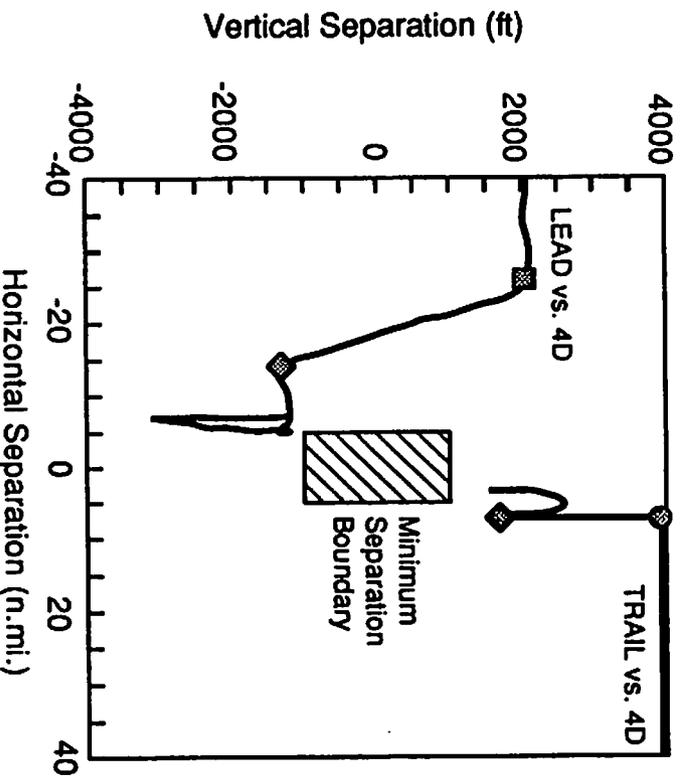
A/C	Speed Profiles (knots)			Top of Descent Marker (Descent Dist to MF, n.mi.)
	Cruise		Descent	
	Indicated	Ground	Indicated	
LEAD	250	413	280	□ (66)
4D (proposal)	250	400	230	◇ (63)
TRAIL	250	427	230	○ (78)
Controller Issued Profiles (conflict-free)				
LEAD	265	436	265	■ (69)
4D	240	384	240	◆ (62)
TRAIL	250	427	240	● (77)

Figure 4. Example arrival scenario.



Top of Descent Marker	
LEAD	□
4D	◇
TRAIL	○

a) Predicted loss of separation based on original vertical profiles (including 4D proposal).



Top of Descent Marker	
LEAD	■
4D	◆
TRAIL	●

b) Resulting separation based on profiles actually flown in simulation.

Figure 5. Separation of the LEAD and TRAIL aircraft from the 4D aircraft for the example illustrated in Figure 4.